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MATERIAL PROPERTIES AND TOLERANCES IN ROLAMITE BANDS

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ABSTRACT

The rolamite band, the most important part of the rolamite geometry, is examined for spring force effectiveness and other important properties. Characteristics of typical band alloys Havar and beryllium copper are presented for various production methods. Also presented are data on production of rolamite bands, and some basic guidelines for rolamite band design.

INTRODUCTION

Rolamite is a revolutionary concept in basic mechanics. Its unlimited versatility presents a new dimension in design to mechanical engineers and designers. The basic rolamite consists of rollers, guide rails for the rollers, and a thin metal band.

Hamilton's association with rolamite began in 1966 when thin metal strip of various alloys was supplied to Don Wilkes at Sandia at the time he invented and developed rolamite. During the past year, Hamilton Precision Metals has produced rolamite strip and bands for several companies actively working on applications which utilize rolamite.

Relative Spring Force Effectiveness of Rolamite Bands

The band is the most important part of the rolamite geometry. Therefore, the choice of the band material must be made carefully in order to optimize the design of a rolamite device. Band materials which permit the lowest band thickness to roller diameter ratios, are in general, the types to specify. Usually, these would be materials which display the highest ratios of yield strain to modulus of elasticity.

Using design information from Sandia Laboratories' Research Report[1] on rolamite, the expression y^3/E^2 can be derived. This ratio of the yield strength cubed divided by the modulus of elasticity squared can be defined as the spring force effectiveness of a rolamite band.

Table I shows the relative spring force effectiveness of various metallic band materials compared to BeCu = 100. If the maximum allowable thickness of BeCu 25 around a given size roller will produce a force of 100 units, the maximum allowable thickness of the alternate material around the same roller will produce the amount of force shown.

Important Properties of Metals Used for Rolamite Bands

Because of the unlimited number of ways in which rolamite can be applied, no single metal will ideally satisfy all the requirements for rolamite bands. As in most design considerations, the selection of an alloy for the rolamite band will involve compromises. The metal to be chosen should be the one which will best satisfy the environmental conditions and functional requirements.

Properties of importance in rolamite band applications are yield strength, modulus of elasticity, endurance limit, corrosion resistance, hardness, electrical resistivity, magnetic properties, thermal expansion, and density. These properties and reasons for their consideration are listed in Table II.

TABLE I

Spring Force Ratings for Eight Materials

Material	Condition	Relative Spring Force Effectiveness
Havar	80% CW and Aged	175
Ti (6Al-6V-2 Sn-Fe)	Aged	110
BeCu 25	80% CW and Aged	100
17-7 PH	CH-900	100
18-8 SS	80% CW	60
Elinvar Extra	80% CW and Aged	50
Mylar (Plastic)		40
Phosphor Bronze D	Hard	30

TABLE II

Important Properties of Metals Used for Rolamite Bands

Property	Reason for Consideration
Yield Strength	Sets limit for maximum allowable band thickness with a given roller diameter.
Modulus of Elasticity	Used in determination of amount of force which can be produced when designing cutouts. Also used in determination of band thickness.
Endurance Limit	Used to determine maximum number of allowable flexures at a given stress level
Corrosion Resistance	Must satisfy environmental conditions (pumping device for corrosive liquids).
Magnetic Properties	Bands, rollers, and guide rails must be nonmagnetic in applications where influence on magnetic fields must be avoided. In some cases bands, rollers, and guide rails can serve as flux paths, in which case, selection should be magnetic materials.
Electrical Resistivity	Electrical contacts and switching.
Thermal Expansion	An important consideration for gaging, instrumentation and thermostat applications.
Hardness	Important for applications involving foreign particles and abrasion.
Density	Could be a consideration in a fluidic balance application.

Quantitative data which are useful in selecting the appropriate metal for rolamite bands are compiled in Table III.

TABLE III

Properties of Materials for Rolamite Bands

	Relative Cost	Yield Strength (psi x 10^3)	Modulus of Elasticity (psi x 10^6)	Stress Endurance Limit (psi x 10^3 for 10^8 cycles)	Corrosion Resistance	Electrical Resistivity (μ-Ω-cm)	Thermal Expansion (μ-in/in/°F)	Hardness (R_c)	Relative Spring Force Effectiveness (force units)
Havar (50% CW and Aged)	2.2	265	30	74	Excellent	94	12.5	55	100
Havar (80% CW and Aged)	2.0	320	30	90	Excellent	94	12.5	60	175
BeCu 25 (H)	1.2	110	17	39	Good	6.5	9.3	20	20
BeCu 25 (AT)	1.6	160	19	36	Good	6.5	9.3	39	55
BeCu 25 (80% CW and Aged)	1.5	195	19	45	Good	6.5	9.3	43	100
Ti (6Al-6V-2 Sn-Fe, Aged)	3.8	180	16		Good	157	5.0	48	110
Elvinar Extra (80% CW and Aged)	1.8	200	27.5	60	Very Good	104	3.9	43	50
17-7 PH (Condition CH-900)	1.2	260	29	80	Good	83	9.5	49	100
Phosphor Bronze D (Spring Hard)	1.0	116	16	29	Good	16	10.2	25	30
18-8 S.S. (80% CW)	1.0	210	27.5	80	Good	73	9.9	45	60
Mylar (Plastic)		13	0.5		Excellent	Insulator			40

CHARACTERISTICS OF TYPICAL BAND ALLOYS

Havar

Havar is a nonmagnetic cobalt base alloy which was developed for watch mainspring applications. It is a high-strength alloy particularly suited for applications involving repeated flexing. It is highly resistant to taking a set even when retained in a flexed position for long periods of time. Havar is not hardenable from the solution-annealed condition. In order to harden Havar, it must first be cold worked. Following a cold working process it can be age hardened by heating to a temperature of about 1000°F for one to four hours. When it is desirable to retain the bright metallic lustre, the hardening operation is done in vacuum. If discoloration can be tolerated, Havar can be age hardened in air without adversely affecting its mechanical properties.

Quantitative data specific to rolamite have not yet been developed. It is noted that the endurance limit data in Table III are obtained from the conventional R. R. Moore[2] rotating beam fatigue tests. Test specimens are shown in Figure 1.

Until quantitative rolamite data are developed, performance of Havar in other flat spring applications can serve as a guide in material selection for rolamite bands. Although some spring steels have a higher stress endurance limit than Havar, it is observed that it was not until the development of the high strength cobalt base alloys that unbreakable mainsprings became available. Because the flexing action of a rolamite band resembles the stressing of a watch mainspring, it is likely that Havar will prove to be the alloy best suited for applications involving millions of cycles at high stress levels. The high corrosion resistance of Havar is a useful characteristic in resisting stress corrosion, since even in the static condition, the rolamite band is under stress where it conforms to the rollers.

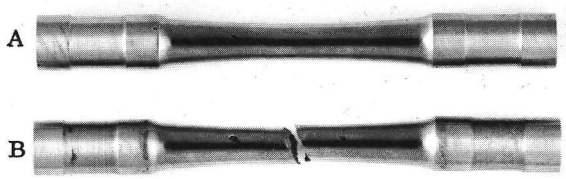

Figure 1A. Test Specimen for R. R. Moore Rotating Beam Fatigue Test
1B. Specimen After Testing to Failure at Stress Level Above the Endurance Limit

The excellent performance of Havar in spring type applications can be attributed to the fact that it is age-hardenable from the cold rolled condition. The microstructure consists of flattened elongated grains resembling laminated platelets. In contrast, the hardened structure of conventional steels has a fine granular texture.

In the solution annealed condition, Havar has an equiaxed grain structure as seen in Figure 2.

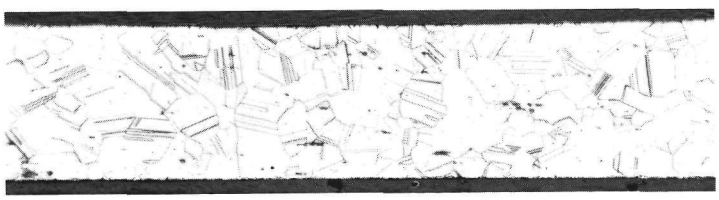

Figure 2. Equiaxed Grain Structure of Solution Annealed Havar (Magn = 100x.)

Cold rolling raises the strength of Havar and produces a laminated texture as seen in Figure 3. Subjecting cold rolled Havar to an age hardening heat treatment further increases the strength without changing the laminated texture. The microstructure of Havar in the age-hardened condition after rolling is seen in Figure 4.

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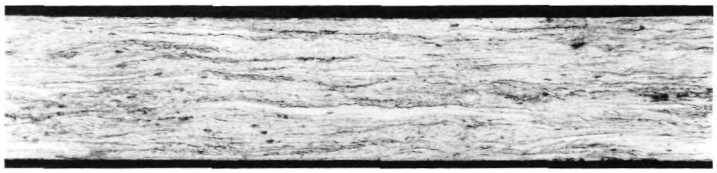

Figure 3. Laminated Grain Texture After 80% Cold Rolling (Magn = 100x.)

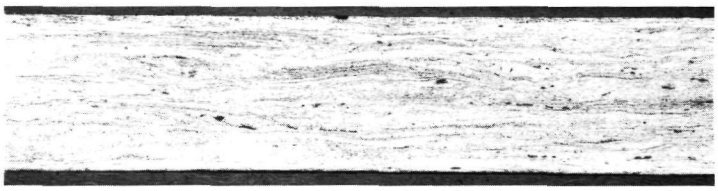

Figure 4. Microstructure of Havar, Cold Rolled 80% and Age Hardened 1 hr. at 1000°F. (Laminated texture remains after age hardening. Magn = 100x.)

Havar Tensile Strength, Yield Strength, and Hardness -- The high strength of Havar is obtained by cold working followed by age hardening. The graph in Figure 5 illustrates tensile and yield strength as a function of cold reduction and heat treatment. The hardness as a function of cold work and heat treatment is illustrated in Figure 6.

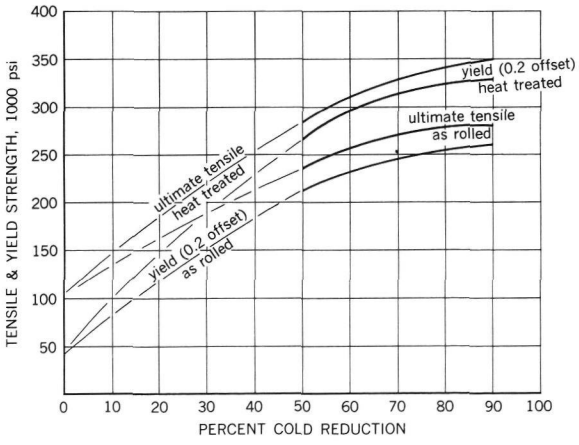

Figure 5. Effect of % Cold Reduction on Strength Properties of .005 Havar Strip "as rolled" and "heat treated at 1000°F"

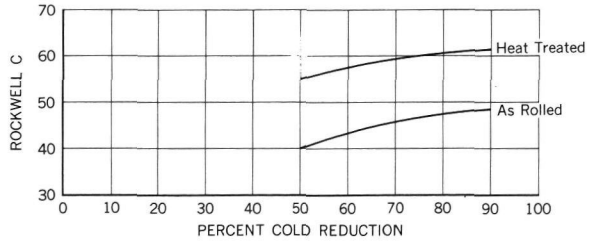

Figure 6. Effect of % Cold Reduction on Hardness of .005 Strip "as rolled" and "heat treated at 1000°F"

Havar Advantages -- The particular advantages of Havar are: (1) high yield strength (above 300,000 psi); (2) high endurance limit (90,000 psi); (3) high modulus of elasticity (30,000,000 psi); (4) high hardness (R_C 60); (5) high corrosion resistance.

Beryllium Copper

BeCu is utilized in many applications requiring spring properties. It can be age hardened from either the annealed condition or from the cold worked condition. A widely used hardening treatment for BeCu is 625°F for two hours in a protective atmosphere. Other time-temperature treatments can be used to change the yield-elongation properties. The proper choice of time-temperature is the one which produces the best functional properties for the application. Tensile, yield, and elongation data as a function of heat treating temperature are shown on Figure 7. Microstructures of BeCu are shown in Figures 8, 9, and 10.

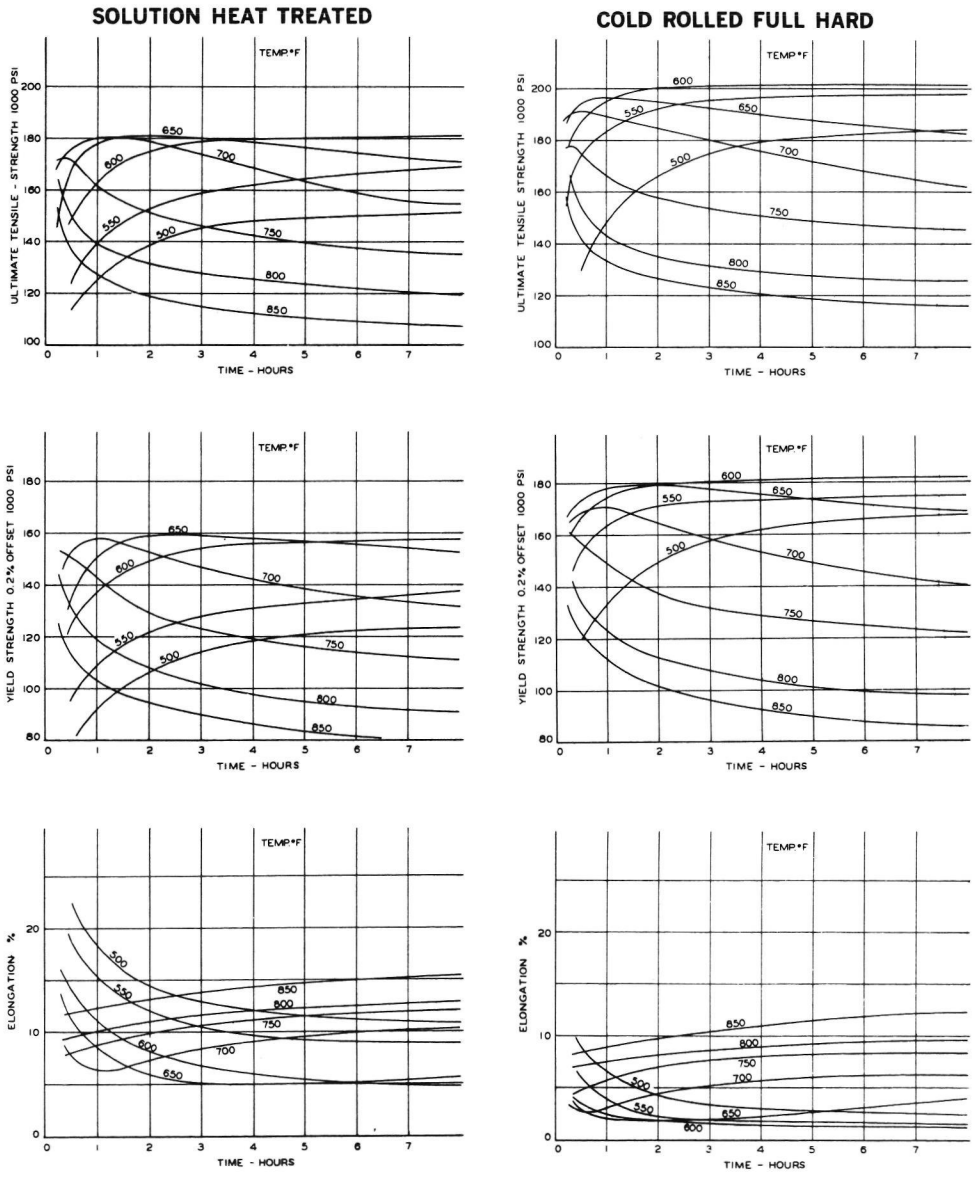

Figure 7. Berylco 25 Alloy, Influence of Age Hardening Time and Temperature on Yield Strength, Tensile Strength and Elongation (Graphs reprinted from Berylco Heat Treatment Bulletin No. 1030-B.)

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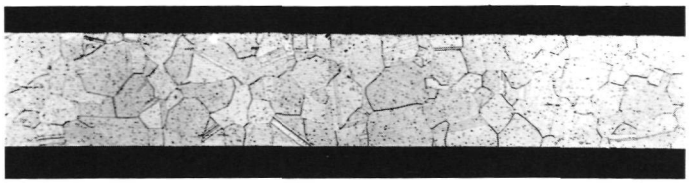

Figure 8. Equiaxed Structure of Annealed BeCu (Magn = 100x.)

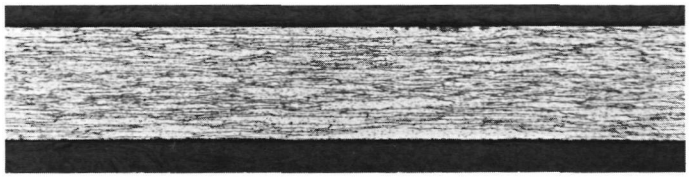

Figure 9. Laminated Texture of BeCu After 80% Cold Rolling (Magn = 100x.)

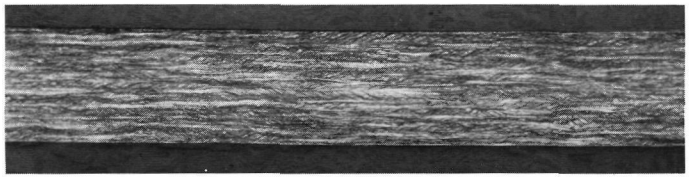

Figure 10. Microstructure of BeCu After 80% Cold Reduction and Age Hardening 1 hr. at 650°F. (Laminated texture remains after age hardening. Magn = 100x.)

Heat Treatment of Some Alloys

The information on heat treatment can be useful in selecting a metal for use at elevated temperatures. BeCu would not be a good choice for operation as a rolamite band if the operating temperature were 500°F or above.

In addition to oxidation, the alloy would continue to age harden and eventually over age. On the other hand, Havar would probably be suitable for use up to 800°F. Recommended heat treating procedures for the seven metals listed in Table III are tabulated in Table IV.

Elevated temperature properties for Havar and several other alloys are shown in Figure 11.

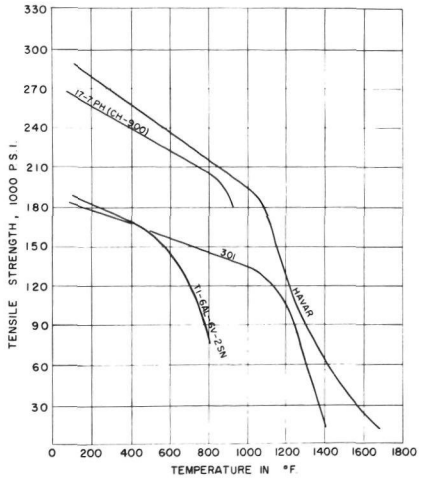

Figure 11. Effect of Temperature on Tensile Strength

Size Availability and Production Tolerances for Rolled Strip

The degree of uniformity of a rolamite system will depend in part on the control of

TABLE IV

Heat Treating Procedures

Havar	Solution treat at 2200°F, water quench. Cold work and age harden at 1000°F for 1 to 4 hours in vacuum. Havar cannot be age hardened from solution treated condition.
BeCu 25	Solution treat at 1500°F, water quench. Age harden from either solution treated or solution treated and cold worked condition. Age harden at 625°F for 2 hours.
17-7 PH (CH 900)	Solution treat at 1950°F. Cold work 60%. Age harden at 900°F for 1 hour.
Elinvar Extra	Solution treat at 1850°F, cool rapidly. Cold work. Age harden at 1250°F for 1 to 4 hours.
18-8 SS	Some improvement in strength properties is obtained by heating cold worked alloy to 900°F for 1 hour.
Phosphor Bronze D	Not hardenable by heat treatment.
Ti (6 Al-6V-2 Sn-1 Fe)	Solution treat at 1650°F for 1 hour and water quench. Age harden at 900-1100°F for 4 to 8 hours.

the dimensions of the strip used to make the band. The rolling tolerances for strip thicknesses ranging from 70 millionths to 0.065 inch are tabulated in Table V. The maximum width of strip is determined by the mill on which the strip is rolled. The minimum width is related to the material thickness and is determined by the capability of the slitting operation. Strip widths for various thicknesses are listed in Table VI. Tolerances on width control are shown in Table VII.

TABLE V

Sizes and Tolerances

Thickness (inches)	Width (inches)	Thickness Tolerances
0.00007 to 0.0004	4 max.	±5%
0.0004 to 0.001	12 max.	±5%
0.0010 to 0.010	12 max.	±0.0001 inch
0.010 to 0.025	12 max.	±0.0002 inch
0.025 to 0.040	12 max.	±0.0003 inch
0.040 to 0.065	12 max.	±0.0005 inch

The width and tolerances may vary depending on properties of alloys being rolled.

TABLE VI

Strip Thickness and Width

Thickness Range (inches)	Width Range (inches)
0.0004 to 0.0008	0.029 min. -14 max.
0.0008 to 0.010	0.029 min. -18 max.
0.010 to 0.020	0.040 min. -18 max.
0.020 to 0.040	0.050 min. -18 max.
0.040 to 0.060	0.080 min. -18 max.
0.060 to 0.080	0.100 min. -18 max.

TABLE VII

Strip Width Tolerances

Thickness (inches)	Under 0.060 Inch Wide (inches)	0.060 to 0.500 Inch Wide (inches)	Over 0.500 Inch Wide (inches)
0.0004-0.005	±0.001	±0.002	±0.005
0.005-0.010	±0.001	±0.003	±0.005
0.010-0.040	±0.002	±0.005	±0.005
0.040-0.080	-	±0.005	±0.005

PRODUCING ROLAMITE BANDS

Photoforming

Photoforming is a process for producing flat, precision parts from thin metals by a combination of photographic and chemical techniques. It affords freedom and flexibility in designing parts and is particularly useful for production of rolamite bands. A variety of burr-free bands produced by photoforming are shown in Figure 12. Some bands have reduced thickness at specific locations to produce desired force effects. Others show cutouts readily obtained by this process. Bands can be photoformed from the metals shown in Table VIII with the tolerances for the various thicknesses as indicated.

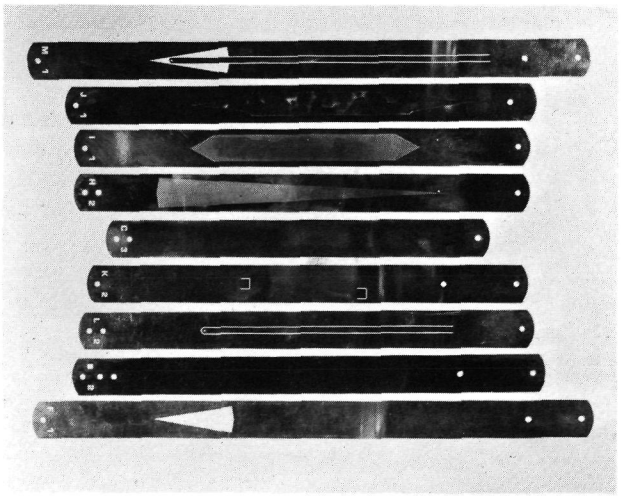

Figure 12. Rolamite Bands

TABLE VIII

Tolerances for Selected Metals at Various Thicknesses

Metals	Thickness (inches)	Tolerance (inches)
Copper and Copper Alloys	0.001 and below	±0.0002
	0.002	±0.0002
	0.004	±0.0002
	0.005	±0.0002
	0.010	±0.0005
	0.020	±0.0020
Havar	0.001 and below	±0.0005
	0.002	±0.0005
	0.004	±0.0005
	0.005	±0.0010
Kovar, Carbon Steels, Nickel Silver, Stainless Steels (300 and 400 Series)	0.001 and below	±0.0004
	0.002	±0.0004
	0.004	±0.0005
	0.005	±0.0008
	0.010	±0.0010
	0.020	±0.0020
Titanium	0.001 and below	±0.0005
	0.002	±0.0010
	0.004	±0.0015

Stress Concentrations[1]

"Features in the band such as cutouts or tapers can impair the strength of the band in two ways. First, they reduce the load carrying areas of the band which produce regions of high stress. Second, these features can introduce stress concentrations which further reduce both the allowable working stress and the fatigure life. These considerations must be taken into account when designing a band with cutouts and tapers."

Photoforming capabilities for a typical rolamite band are shown in Figure 13.

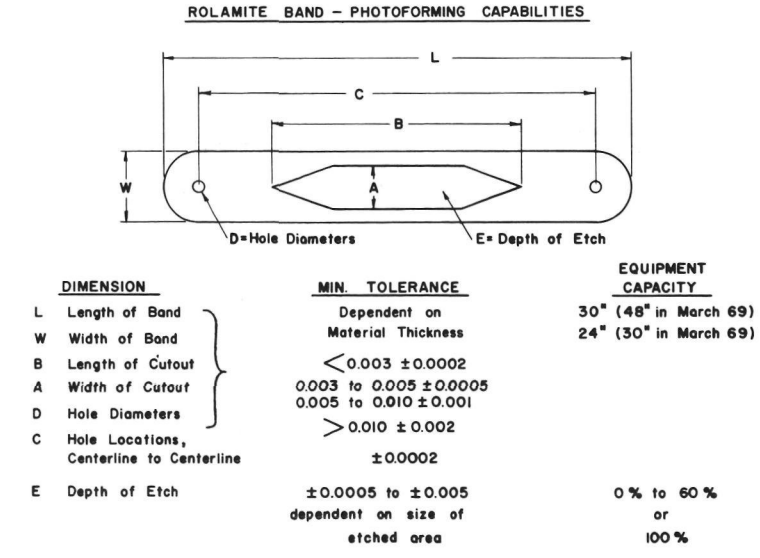

Figure 13. Rolamite Band - Photoforming Capabilities

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ROLAMITE BAND DESIGN FORMULAE

Calculating Band Thickness

Shown in Figure 14 is a portion of a typical rolamite assembly consisting of a single roller of diameter d and an encircling band of thickness t; the band thickness is exaggerated for clarity. The band tension, T, forces the flexible band to conform to the diameter of the roller. This flexing requires that the inner fibers of the band be compressed and the outer fibers be expanded. At some central position, known as the neutral axis, the fibers retain their original length. The actual location of this neutral axis depends on the overall stress situation including the effects of the band tension. However, the stress due to band tension is typically less than 1 percent of the maximum stress due to flexing around the roller. Therefore, to a close approximation the neutral axis is located at the center of the band thickness. The total length of the neutral axis is:

$$l_n = \left(\frac{d}{2} + \frac{t}{2}\right)\theta \qquad (1)$$

where:

l_n = length of neutral axis, inches

d = roller diameter, inches

t = band thickness, inches

θ = wrap angle, radians

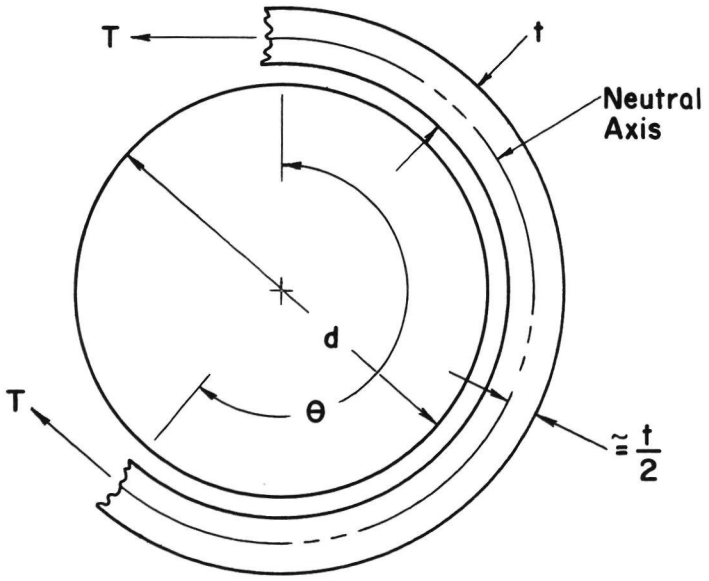

Figure 14. Free Body Diagram of Roller and Band

Similarly, the length of the outer surface is:

$$l_o = \left(\frac{d}{2} + t\right)\theta \tag{2}$$

Strain (ϵ) is defined as the change in length divided by the original length, and since maximum strain occurs on the outer surface:

$$\epsilon_{max} = \frac{l_o - l_n}{l_n} \tag{3}$$

Substituting Equations 1 and 2 for l_n and l_o in Equation 3,

$$\epsilon_{max} = \frac{t}{d + t} \tag{4}$$

From Hooke's Law for elastic behavior, stress (σ) is equal to the product of strain (ϵ) times Young's modulus.

$$\frac{\sigma}{\epsilon} = E \qquad\qquad \sigma = \epsilon E \tag{5}$$

Assuming that the allowable stress is restricted to the yield stress of the band material, substitution of Equation 4 yields an expression for the maximum band thickness:

$$t_{max} = \frac{\sigma_y d}{(E - \sigma_y)} \tag{6}$$

For most engineering materials, the yield stress is much smaller than the modulus of elasticity and to a close approximation:

$$t_{max} \approx \frac{\sigma_y d}{E} \tag{7}$$

and for a roller diameter of one inch

$$t_{max} \approx \frac{\sigma_y}{E} \tag{8}$$

This analysis has assumed that the band was initially flat. (Precurved bands would alter the location of the neutral axis.) Also it should be noted that the fatigue life was not taken into account; this consideration would reduce the value of allowable thickness. If band thickness is to be maximized for a given roller diameter, the band material should be selected to provide a large ratio of yield stress to modulus of elasticity.

The materials which best meet this criterion include the metals commonly used in springs and several of the plastics. The plastics, although allowing larger thicknesses, do have the disadvantages of low strength, plastic "creep," undesirable aging characteristics, and poor stability under changing temperatures.

MATERIAL PROPERTIES AND TOLERANCES IN ROLAMITE BANDS

Band Force Generation

One of the most valuable aspects of the rolamite geometry is the ability to produce forces by band contouring. To a close approximation, the force provided by band contouring within an assembly having equal-sized rollers is:

$$F = \frac{Et^3 (b - a)}{6d^2} \tag{9}$$

where:

F = generated force, pounds

(b - a) = cutout width (difference in local band width at upper and lower roller - guide contact points, inches)

From this equation it is seen that the generated force depends upon the cube of the thickness. Thus, accurate force generation requires that the thickness be controlled very carefully. This includes edge effects such as slitting burrs and crown. Maximum band thickness is very important in the determination of maximum forces available. Substitution of Equation 7 into Equation 9 results in:

$$F_{max} = \frac{\sigma_y^3 \, d(b - a)}{6 E^2} \tag{10}$$

Accordingly, the maximum force available is directly proportional to the cube of the yield strength and inversely proportional to the square of the modulus of elasticity. This ratio can be defined as the "material effectiveness":

$$\text{Material Effectiveness} = \frac{\sigma_y^3}{E^2} \tag{11}$$

As an example, Berylco 25, when in a hard and aged condition, exhibits a material effectiveness of approximately 20. Since this is a commonly used material within rolamite design, it might be considered as a "reference" and we can define "relative material effectiveness" as follows:

$$\text{Relative Material Effectiveness} = \frac{\text{Other Material Effectiveness} \times 100}{\text{Material Effectiveness of Berylco 25}}$$

An interpretation of relative material effectiveness is as follows: "If it can be assumed that for a given band cutout and roller diameter, the maximum allowable thickness of beryllium copper 25 produces a force of 100 grams, the maximum allowable thickness of the alternate material under the same conditions will produce a force in grams equal to the relative material effectiveness." Once again, it is found that the metals commonly used as spring materials are most effective. The final choice of course would be dependent upon cost, ease of fabrication, and other desired properties.

It is interesting to note that among the commonly available plastics only Mylar has a relative material effectiveness of significant value. Mylar is useful as a band material in prototype models. Since it is easily contoured with any sharp cutting instrument, a prototype band can be quickly generated. On the other hand, the aforementioned disadvantages of any plastic material are present.

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1. Wilkes, D. F., Rolamite: A New Mechanical Design Concept, SC-RR-67-656A, December 1967.

2. Moore, H. F., Fatigue Tests, ASM Handbook, 1948 Edition, pp. 118-124.